NOTICES

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any employees, nor any of their contractors, subcontractors, or their employees, make any warranty, expressed or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency, contractor, or subcontractor thereof. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency, contractor, or subcontractor thereof.

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

Neil J. Lamb.

JOSEPH D. WANDER
Project Officer

NEIL J. LAMB, Colonel, USAF, BSC
Director, Environics Directorate

Edward N Coppola

EDWARD N. COPPOLA, Major, USAF
Chief, Environmental Compliance Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	930917	Final; 9302 to 9304

4. TITLE AND SUBTITLE
LABORATORY EVALUATION OF A REACTIVE BAFFLE APPROACH TO NOx CONTROL

5. FUNDING NUMBERS
F08635-90-C-0053/P00003
JON 3005 0033
PE 65502F

6. AUTHOR(S)
S.G. Nelson, D.A. Van Stone, R.C. Little, and K.A. Peterson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Sorbent Technologies Corp
1935 E. Aurora Road
Twinsburg OH 44087

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Armstrong Laboratory, Environics Directorate
AL/EQS-OL
139 Barnes Drive, Suite 2
Tyndall AFB FL 32403-5323

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AL/EQ-TR-1993-0017

11. SUPPLEMENTARY NOTES
Project Officer: Joseph D. Wander (904) 283-6240/DSN 523-6240

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)* This report describes a study to evaluate the feasibility of inserting a special material inside the baffles in the chimneys of jet-engine test cells (JETCs) to control NOx emissions. In previous research conducted by Sorbent Technologies Corporation, three materials--expanded vermiculite, activated carbon, and MagSorbent (MgO-coated vermiculite)--demonstrated the ability to sorb or reduce the levels of NOx in JETC exhaust gases. These three materials were examined in this study.

Atest setup was designed, constructed and installed in the laboratory to simulate the passage of gas up through baffles in JETCs. With this test setup, a series of runs was performed to determine how changes in exhaust-gas variables and in baffle design affect NOx removal performance.

Jet-engine exhaust gases in test cells are normally heavily diluted with air before they are expelled to the atmosphere. The compositions of exiting gases therefore are similar to that of air, except for additions of NOx, particulates, water and CO. Most runs in the project were performed with air to which measured amounts of NOx were added. Two runs near the end included CO in addition to NOx.

14. SUBJECT TERMS
Turbine engines; Air Pollution; NOx emissions

15. NUMBER OF PAGES
46

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18
298-102

13. Abstract (Continued)

All three materials that were studied captured or removed some NOx from the simulated exhaust gases. Removals were observed both by chemical analyses of gases entering and leaving the test units during the runs and by chemical analyses of released gases during desorption studies after the test runs.

The removals with vermiculite and MagSorbent were relatively low. With vermiculite, removals ranged from zero to about 14 percent, with about 3 percent being the average; with MagSorbent, removals ranged from zero to about 7 percent, with an average of 4 percent at low velocities and 1.5 percent at high velocities. In one run with gases at low velocities and with CO in the entering gas streams, both the NOx and the CO levels were reduced up to 35 percent by exposure to MagSorbent. Vermiculite exposed to high-velocity gas streams containing CO, however, did not reduce NOx levels significantly.

Activated carbon was fairly effective in reducing NOx levels. Typically, NOx removals of 10 to 33 percent occurred. With activated carbon, NOx removal performance decreased with increasing exhaust-gas velocity. Over the temperature range, 70° to 300°F, the NOx removal rate was generally constant for a given gas velocity.

The total surface area and configuration of the baffle surface appeared to have only minimal effect on NOx removal. Rounded and flat surfaces gave about equal performance. Changing the spacing between plates to increase turbulence generally did not significantly increase NOx removals. On the other hand, contact time, as influenced by the velocity of the exhaust gas and the length of the baffle, did affect NOx removal performance.

PREFACE

This report was prepared by Sorbent Technologies Corporation (Sorbtech), 1935 East Aurora Road, Twinsburg, OH 44087, under DOD Small Business Innovation Research Contract No. F08635-90-C-0053; P00003, for the Air Force Civil Engineering Support Agency (HQ AFCESA/RAVS, formerly the Air Force Engineering and Services Center [HQ AFESC/RDVS]) 139 Barnes Drive, Tyndall AFB FL 32403-5319.

This final report describes a short laboratory study that examined the technical feasibility of employing a modified sound-suppressing baffle to reduce NOx during tests in a jet engine test cell (JETC). The work was performed between February 1993 and April 1993. The Air Force project officer was Dr. Joseph D. Wander.

The authors, Sidney G. Nelson, David A. Van Stone, Robert C. Little and Kenneth A. Peterson, were members of the research staff at Sorbtech.

(The reverse of this page is blank)

EXECUTIVE SUMMARY

A. OBJECTIVE:

Vermiculite, vermiculite coated with magnesia, and activated carbon sorbents have successfully removed NOx (and carbon monoxide and particulates) from combustion exhausts in a subscale drone jet engine test cell (JETC), but back pressure so generated elevated the temperature of the JETC and of the engine. The objective of this effort was to explore the feasibility of locating the sorbents in the face of the duct or of baffles parallel to the direction of flow within the ducts.

B. BACKGROUND:

Jet engine test cells (JETCs) are stationary sources of oxides of nitrogen (NOx), soot, and unburned or partially oxidized carbon compounds that form as byproducts of imperfect combustion. Regulation of NOx emissions is being considered for implementation under the Clean Air Act Amendments of 1990.

Several principles have been examined as candidate methods to control NOx emissions from JETCs. However, the JETCs operate as grossly non-steady-state sources, which disqualifies most catalytic approaches; temperatures compatible with catalytic or noncatalytic reduction occur over short distances within the augmentor tube, in which the engine thrust creates extreme mechanical stresses; and modern engines are relatively sensitive to back pressure and to changes of temperature. A second condition--that no hazardous materials be used or formed--excluded all candidates tested to date except for three, low-temperature materials: vermiculite, vermiculite--MgO, and activated carbon (which may become a hazardous waste at the conclusion of service). Bench, prototype, and pilot tests of these three materials suggested that any or all of them could be used to control NOx from JETCs if the back pressure could be eliminated.

C. SCOPE:

During this study, three basic configurations--flow through a circular section surrounded by an annular bed of sorbent, passage between parallel flat baffles, and passage between flat baffles defining a tapering cross-section (to enhance turbulence)--were examined at a range of temperatures, face velocities, and plate separations. NOx removal was measured as a function of the preceding process parameters and of time. This report details work performed during the months of February and March, 1993, under amendment P00003 to Contract F08635-90-C-0053.

D. METHODOLOGY:

This was strictly a bench-scale study. The exhaust from a gas burner was spiked with nitric oxide (NO) and drawn through a forced-draft blower into a test section. A commercial cell analyzer was used to monitor concentrations of oxygen, NOx, and CO in gas samples drawn from ports immediately before and after the test section. Two test sections were fabricated: one was a right cylindrical structure in which a concentric cylindrical screen defined an annular bed surrounding the flow; the second was a set of eight half-rectangular segments that fit together in pairs to define a rectangular duct. The sorbent was contained behind a screen enclosing the walled end of each half-rectangular segment. The width of the space between the two screens in an assembled pair of segments could be adjusted by sliding the segments apart or together at either end.

E. TEST DESCRIPTION:

After shakedown, the cylindrical section was inserted and a series of seven tests were run, lasting from 15 to 45 minutes. After replacement of the cylindrical section by the rectangular section, the inner dimension was adjusted to a uniform value for three runs, then pinched at the ends and middle to create a tapering section, in which configuration six runs were made. The last run in the cylindrical and tapered configurations included additions of CO and NOx to the exhaust. For all runs, exhaust temperature, temperature downstream of the test section, pressure drop across the test section, face velocity of the gas, and concentrations of NOx before and after treatment were recorded.

F. RESULTS:

Fair removal (<30 percent) was observed at minimal flow rates in the presence of added CO. For all other runs, removal averaged a few percent and the pressure drops were consistently between 0.1 and 0.2 inches (W.G.). Of the sorbents, carbon was the least ineffective, reaching removals in excess of 10 percent at the lowest flow rates. Liberations of NOx by heating appeared to occur efficiently at reasonable temperatures for coated vermiculite and for carbon.

G. CONCLUSIONS:

Peripheral exposure of the gas stream to the three treatments tested is significantly less effective than direct passage through a fixed bed of the same materials. The extent of removal is too low to support development of a treatment technology. However, if modest enhancement of removal by another method is needed, enclosure in baffles may have value as a polishing treatment for flue gases. That NOx release from heated vermiculite was minimal and that CO enhanced removal suggests that vermiculite acts as a catalyst rather than a sorbent.

H. RECOMMENDATIONS:

Application of fixed beds of these or related sorbents will require a large increase in the cross-sectional area of the bed, augmentation of the pressure drop by an extractive blower, or both for application to a practical JETC. Development of sufficient bed area may require redesign of the JETC and construction from the ground up. The previous estimate of $3 a pound to remove NOx is probably an underestimate.

TABLE OF CONTENTS

(The reverse of this page is blank)

SECTION I

INTRODUCTION

A. PROJECT OBJECTIVES

Pending action to regulate emissions of NOx from jet engine test cells (JETCs) (among other sources) has created an immediate need for information about the practicability and cost of applying NOx-emission control technologies to JETCs. CEL-TR-92-49* details a qualitatively successful development and demonstration of three reactive sorbents able to remove NOx from high-velocity, nonsteady-state combustion exhaust streams. This report describes a series of experiments undertaken to decrease the impact of back pressure caused by the same three sorbent materials on the operation of the JETC and the engine during testing. The specific objective of this component was to determine the feasibility of locating the sorbent next to the exhaust stream rather than obstructing its flow.

B. BACKGROUND

This is the eighth in a series of investigations into the chemistry and engineering of NOx controls compatible in JETCs, a high-velocity, rapidly-changing environment that is intolerant of back pressure. In an earlier phase of this project, three materials, expanded vermiculite, activated carbon, and a combination of MgO and vermiculite, were demonstrated to reduce the levels of NOx present in exhaust gases. The levels of NOx were reduced when jet-engine test-cell (JETC) exhaust gases containing NOx were allowed to pass through individual panel beds or combinations of beds of these materials placed at the end of the test-cell exhaust system. However, back pressure raised the temperature of the JETC and the engine significantly.

A simple alternative to a tail-end panel bed to control the NOx levels of JETC exhaust gases consists of filling baffles located parallel to the flow with a material or compound that readily sorbs and removes the NOx in exhaust gases. The earlier results with expanded vermiculite, activated carbon, and MgO-coated vermiculite suggest that one or all of these materials might be candidates. All three materials, like steel wool (presently used), are expected to exhibit good sound-suppressing properties. Substituting one of these materials for steel wool in baffles could be an inexpensive approach to achieve NOx reductions.

Baffles in older test-cell chimneys typically are 8 to 12 inches wide, 20 feet or more long and 16 feet or more high. The baffles are placed in a parallel arrangement that fills the total chimney cross-section. Between the flat baffle faces are 8- to 12-inch open spaces through which the exhaust gases pass. Steel wool is physically contained inside the individual baffles. If this steel wool were replaced by a second material and uniform, parallel flow occurred between baffles, only a small portion of the replaced material (its exposed bed surfaces) would be expected to contact the exhaust gases passing up through the spaces between baffles. However, with turbulent flow, perhaps much more contact might be induced.

---

*Nelson, B. W., Van Stone, D. A. and Nelson, S. G., Development and Demonstration of a New Filter System to Control Emissions During Jet Engine Testing, Environics Division, Tyndall AFB, FL, CEL-TR-92-49, October, 1992.

Sorbtech researchers measured the velocity of exhaust gases passing up between baffle plates at Tyndall AFB's drone-engine test cell during test runs. As one might expect, the gas velocity varied widely with the phase of testing. During the idle phase, gas velocities were generally low; during full load, they were high. During normal testing, a typical high gas face velocity was about 14 feet per second (fps). At such a face velocity, one can expect a high degree of turbulence in the flow of gases between the baffles. For the baffle configuration at Tyndall AFB, turbulent flow is calculated to occur with gas face velocities of about 3 feet per second or more.

C. SCOPE

This report describes a complete laboratory evaluation of NOx removal efficiency for several off-axis configurations of sorbent beds in a simulated combustion exhaust stream. As these include flow conditions ranging from near-laminar to highly turbulent, the conclusions drawn about the applicability of reactive baffles as a NOx-removal method are considered general. For the convenience of the reader, project data are compiled in the Appendix.

SECTION II

EXPERIMENTAL APPROACH

Work on the project was performed in a series of eight steps:

(1) Test-Shape Design
(2) Sorbent Preparation
(3) Test-Shape Fabrication
(4) Flue-Gas Test-Facility Modification
(5) Test Series 1--Round Channels
(6) Test Series 2--Rectangular Channels
(7) Test Series 3--Modified Rectangular Channels
(8) Evaluation and Reporting

A. TEST-SHAPE DESIGN

Long, narrow structures were designed. One design (Design 1) consisted of an 8-foot-long, 4-inch diameter steel tube, inside of which was placed a cylindrical screen. The general design of this structure is shown in Figure 1. Sorbent was placed into the space between the screen and the tube's inside wall. During testing, simulated exhaust gas was passed through the center of the tube. The screen employed in all structures was made of carbon steel and was 10-mesh, with an open area of 43.3 percent.

A second design (Design 2) consisted of an 8-foot-long, 6-inch by approximately 3-1/2-inch steel assembly, inside of which was welded in place steel screens. The screens covered two of the four inside surfaces, as shown in Figure 2. Sorbent was placed between the screens and the inside surface of the flat plates. During testing, simulated exhaust gas was passed up through the central, open rectangular channel between the two screens.

The structure of Design 2 was actually designed as four separate 2-foot-long, approximately equal parts, where the four parts were assembled to form one complete unit.

A third design (Design 3) was a modified form of Design 2. This design included two areas of constricted flow to increase turbulence in the gas stream as the gas passed through the structure. Figure 3 shows the design, which, like Design 2, consisted of four parts assembled into one unit.

B. SORBENT PREPARATION

Three sorbent materials were evaluated in the project:

(1) Expanded Vermiculite--Coarse grade, obtained directly from Strong-Lite Products Corporation, Pine Bluff, Arkansas. The ore was imported from Africa and expanded in the U.S.

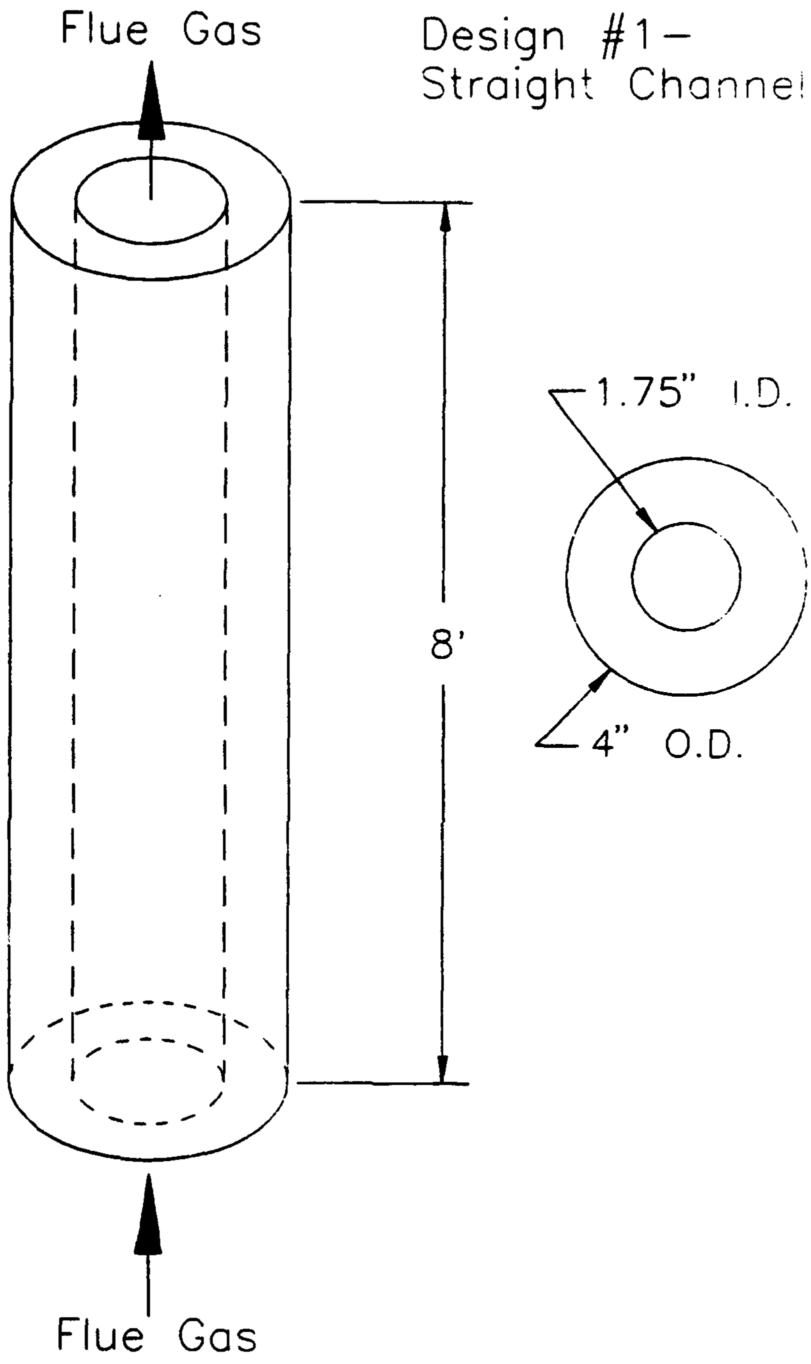

Figure 1. Straight, Round, Open-Channel Design

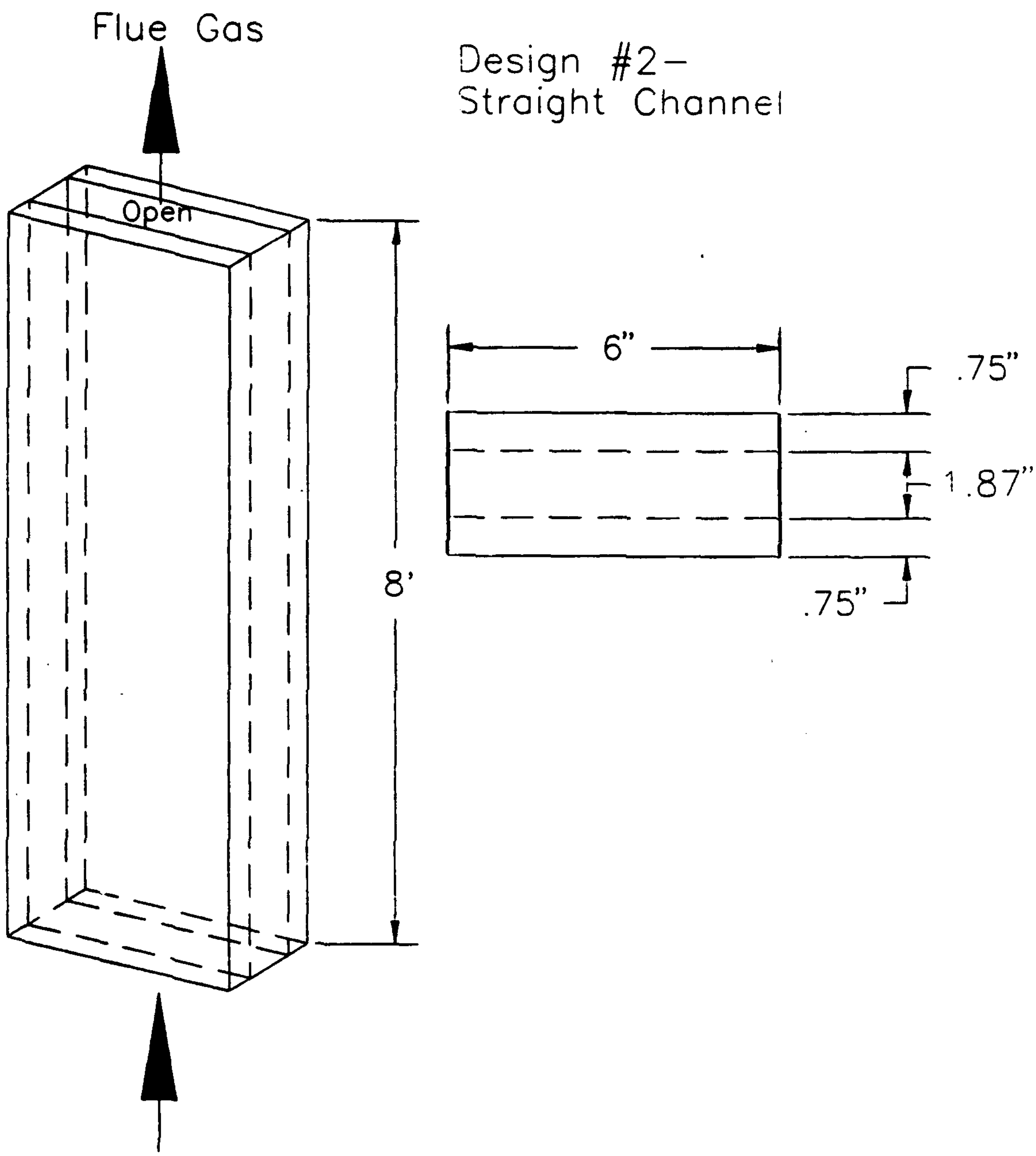

Figure 2. Straight, Rectangular, Open-Channel Design

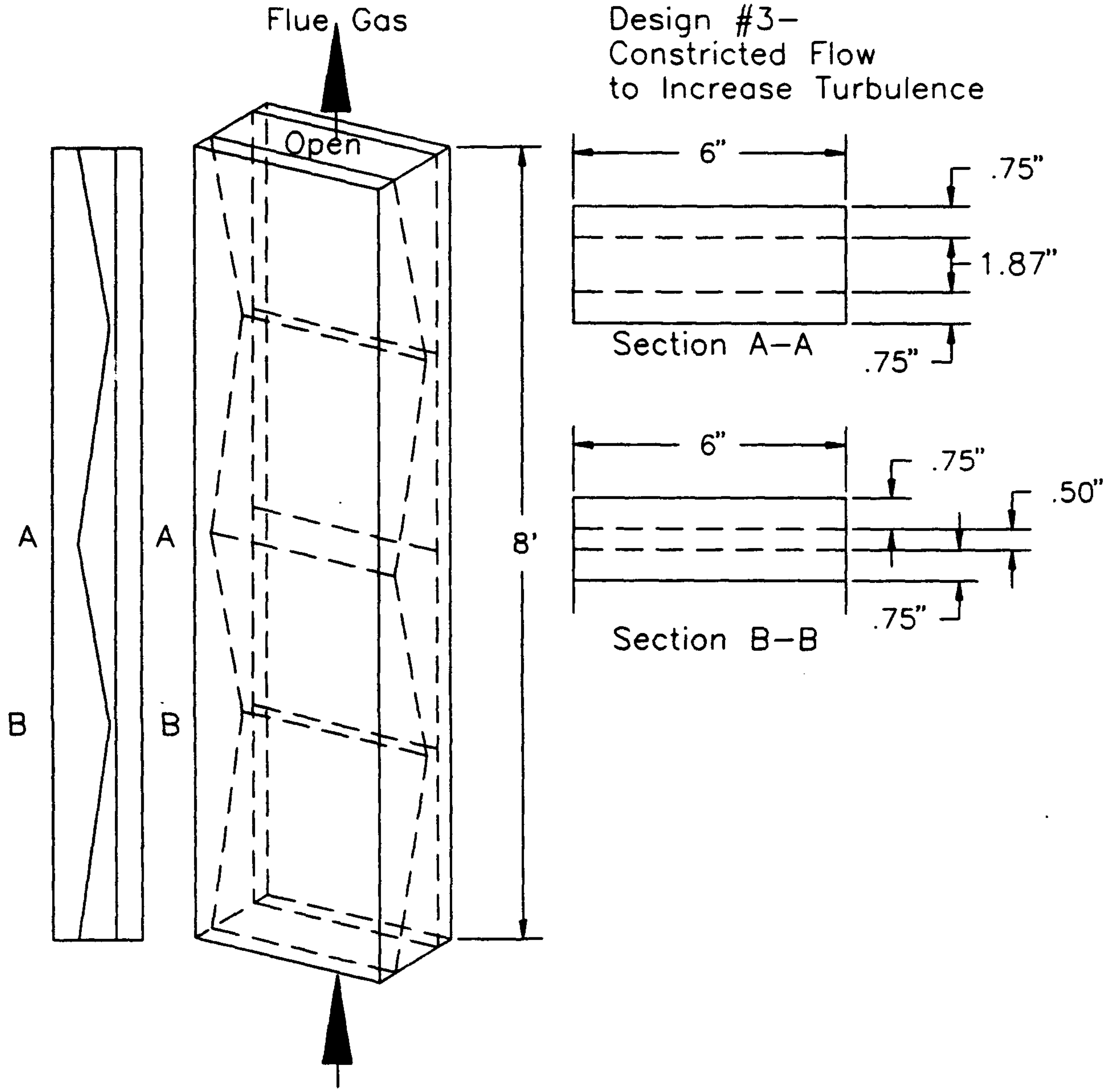

Figure 3. Rectangular, Open-Channel Design with Venturis

(2) Activated Carbon--Grade F816, obtained originally from Calgon Carbons, Pittsburgh, PA. This carbon was used material which had been previously exposed for nine months at Tyndall AFB.

(3) MgO-Coated Expanded Vermiculite--Fresh material consisting of 50 weight percent MgO and 50 weight percent Therm-O-Rock (Pittsburgh, PA) coarse-grade vermiculite. This material was prepared using procedures described in U.S. Patent No. 4,721,582 (assigned to Sorbtech).

C. TEST-SHAPE FABRICATION

Materials for the test shapes were purchased and the test shapes were fabricated by L & L Fab Company of Streetsboro, Ohio. L & L Fab was the low bidder and fabricator of the prototype filter installed at Building 239 at Tyndall AFB during the earlier project.

Figure 4 shows a drawing of the three test structures after fabrication and assembly.

D. FLUE-GAS TEST-FACILITY MODIFICATION

Small modifications were necessary in Sorbtech's existing flue-gas test facility to carry out the planned experiments. These modifications included: (1) Relocating an existing fan to draw exhaust gas from an existing gas heating system; (2) Adding and redirecting pipework to pass gas through the planned test shapes; (3) Installing exit ducting to an exit stack; and (4) Adding the required instrumentation to the system to monitor performance. In the latter case, equipment to measure gas velocities and compositions into and out from the test shapes and pressure drops across the units was installed. No major new equipment or instruments were needed for the project. All items were on hand in Sorbtech's laboratories.

E. TEST SERIES 1--ROUND CHANNELS

Seven test runs were performed using the test shape of Design 1. After an initial shakedown run, variables affecting NOx-removal performance included exhaust-gas temperature and exhaust-gas velocity. In addition to exhaust-gas temperatures and velocities, properties monitored during the runs included the NOx levels of the exhaust gas entering and leaving the test shapes, the temperature of the exhaust gas entering and leaving the test shapes, and the pressure drop across the test shapes. The experimental arrangement that was employed is shown schematically in Figure 5.

The NOx, oxygen, and CO levels of the exhaust gas into and out from the test assemblies were monitored continuously with an Enerac 2000 chemical cell analyzer. Periodically, bag samples of gas were collected and were analyzed separately, both with a chemical cell analyzer and with Kitagawa length-of-stain tubes. In all cases, the analyses performed by these two methods agreed well. The Enerac 2000 was also tested periodically on standard gases in the laboratory. Again, good agreement was observed.

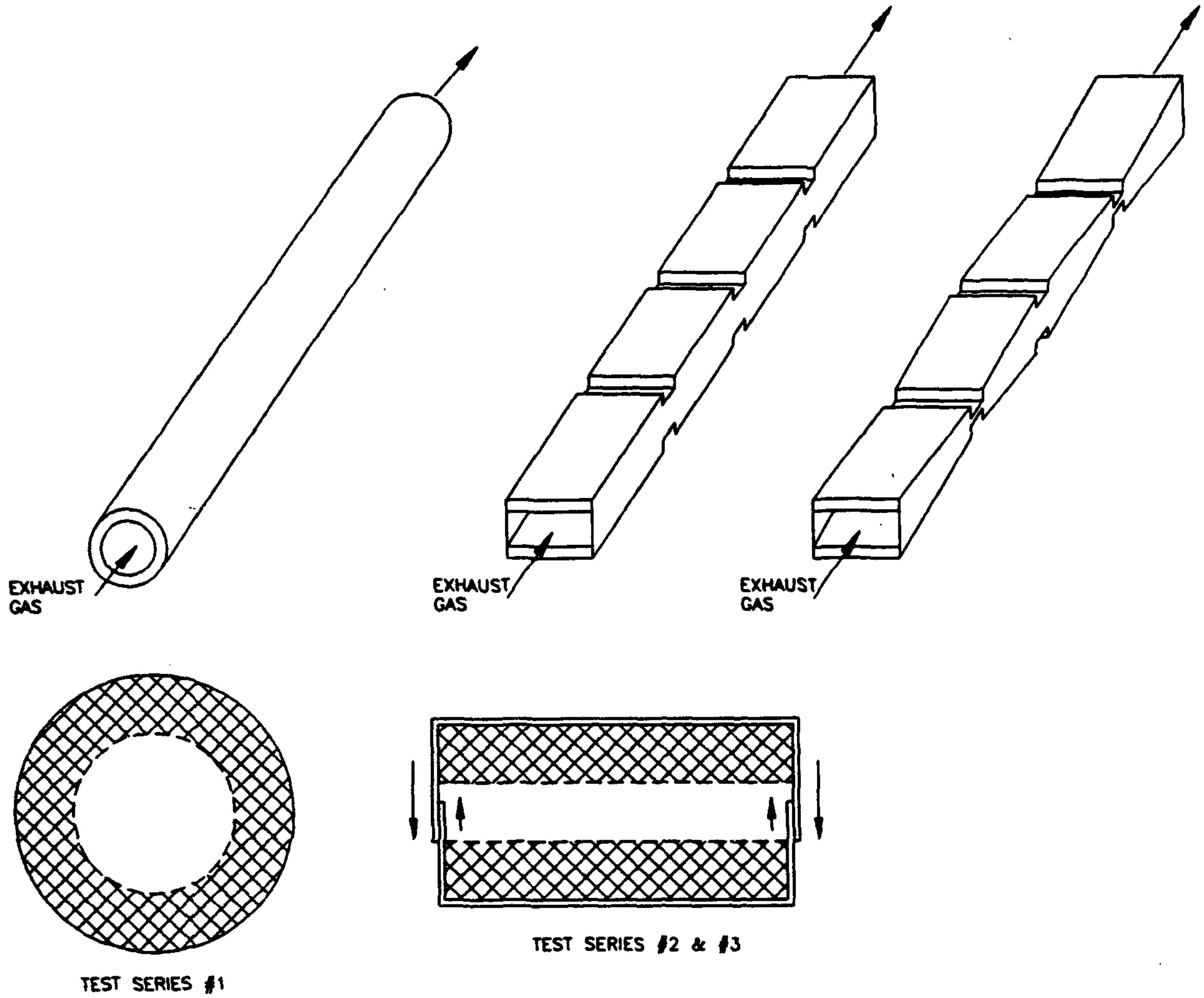

Figure 4. Three Test Structures Employed in the Project

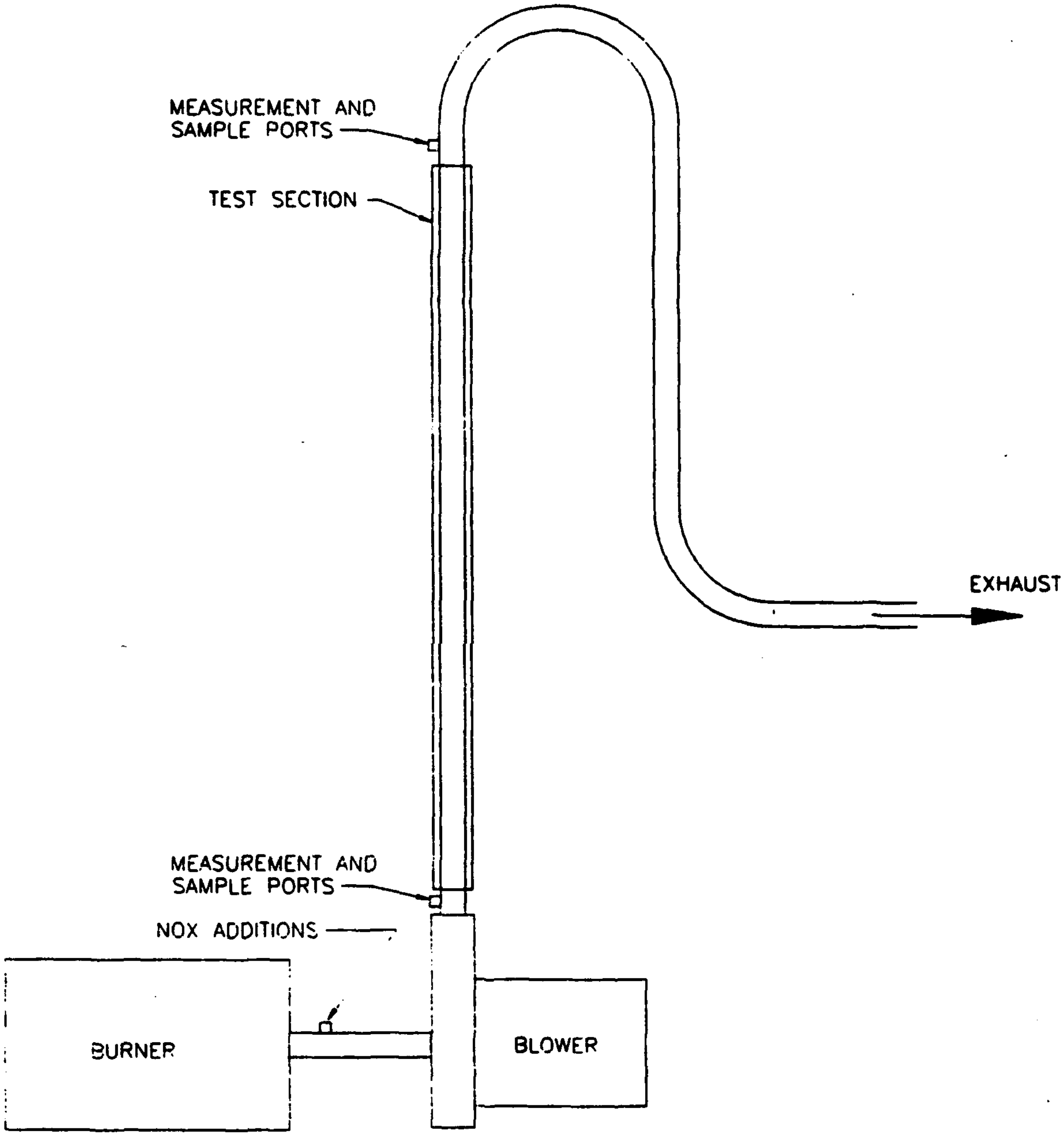

Figure 5. Experimental Arrangement

F. TEST SERIES 2--RECTANGULAR CHANNELS

Following the round-channel tests, the round-channel structure was removed from the test system and was replaced with the rectangular-channel structure, which had been filled with sorbent beforehand. Three runs were performed in this test series, one run with each sorbent material. In these tests, exhaust gases were passed straight through the structures, which possessed a uniform channel. The open-channel dimensions for each test was 6 inches by 1.875 inches. The same processing variables examined in round-channel tests were then investigated in rectangular-channel tests.

G. TEST SERIES 3--MODIFIED RECTANGULAR CHANNELS

The rectangular channel unit was modified so that gas flow through the unit was gradually constricted and expanded at two locations along its path. Four runs were then performed with this modified unit with two venturis. Two runs were performed with MagSorbent (one with NOx additions alone and one with both NOx and CO additions to the gas stream); one run was performed with vermiculite and one run was carried out with activated carbon.

SECTION III

RESULTS AND DISCUSSION

The results are presented in Tables 1 through 14, which appear in the Appendix.

A. MAGSORBENT TEST RUNS

In prior research, MagSorbents were observed to be effective in removing NOx from waste gases when the gases were passed directly through fixed sorbent beds. Removals were particularly high when beds were large and gas face velocities were low. For example, for a 12-in MagSorbent bed and a 1.5 fps flue gas, a NOx-removal efficiency of 30 to 40 percent was common. For a similar bed and flue gases having velocities greater than 8 fps, the NOx-removal efficiency often approached zero.

Several different mechanisms of NOx removal are believed operable when MagSorbents are employed. Principal among these mechanisms is a chemical reaction between NOx and MgO, resulting in the formation of magnesium nitrate. The latter has been the only nitrogen compound identified spectrographically. Some NOx is believed to be captured in the micropores of the MgO coatings, which have been observed through an electron microscope to consist of millions of tiny crystals.*

The scheme examined in this project, that is, passing the exhaust gases <u>across</u> a bed surface is significantly different from passing gases <u>through</u> sorbent beds. As a result, different removals can be expected.

Relatively low gas velocities, 1.1 to 2.2 fps, were employed in the initial test runs that were performed using the sorbent-lined, round, open-channel test unit (See Tables 1 and 2 in the Appendix). With these low gas velocities, NOx removals ranged from 3 to 4 percent. There were significant changes in gas temperature as the gases passed through the test unit, indicating that the gas was making much direct contact with the test unit, and more particularly, with the MagSorbent lining.

Increasing the temperature of the gas up to about 300°F did not appear to affect NOx-removal performance. Increasing the velocity and flow rate of the gas, however, did affect NOx-removal performance. NOx removals with gas velocities above about 3.4 fps were essentially zero (See Table 3).

The results with rectangular channels were similar to those with circular channels. All NOx removals were generally low. The NOx removals with irregular channels (channels made with varying cross-sections to increase turbulence) appeared to be higher than those with straight open channels, but the differences may not have been real.

---

*This work was performed by Drs. Bacon and Ruch of Kent State University and was reported in a paper entitled, "The Physical Nature and Chemical Reactivity of a Heterogeneous MgO/Vermiculite Flue-Gas Sorbent," presented at the 200th ACS National Meeting, Washington, D.C., 1990.

The presence of CO in the exhaust gas clearly improved NOx removal performance for the MagSorbent material. Unfortunately, only a single CO run with MagSorbent near the end of the project was performed. The data for this run are given in Table 11. NOx removals as high as 35 percent were achieved during the run, with parallel removals of CO, as well. Near the end of this run, the oxygen level of the gas was observed to increase slightly as it passed through the test unit (Oxygen levels of the gas were closely monitored during all test runs). This indicated that a small leak may have developed in the system during the run.

B. VERMICULITE TEST RUNS

The results with vermiculite were similar to those observed with MagSorbent. NOx removals were generally low, except for room-temperature gases at low velocities in the rectangular channel unit having venturis. Under these conditions, removals averaged more than 10 percent (See Table 10). Under most other conditions, the gases passed across the vermiculite bed surfaces with very little change in composition.

C. ACTIVATED CARBON TEST RUNS

The activated carbon investigated was effective in reducing the NOx levels of the simulated exhaust gases. NOx removals upon passing over activated carbon surfaces ranged from about 10 percent to 33 percent. The highest rates were observed with low velocity gases at room temperature in the rectangular channel unit having a varying cross-section. NOx removal performance with activated carbon did not appear to change significantly with increasing temperature up to about 300°F. It did, however, appear to change (to decrease) somewhat with increasing gas velocities.

D. GENERAL DISCUSSIONS

After all runs were completed, samples of exposed MagSorbent, vermiculite, and activated carbon were employed in desorption experiments. In these experiments, a 10-gram sample of each material was placed inside an evacuated quartz tube and the sample and tube were heated slowly while nitrogen gas was passed over the sample and the composition of the gases leaving the quartz tube was continually monitored. Particular attention was given to NOx releases.

Figures 6, 7 and 8 show the NOx concentration of the gases leaving the tubes containing MagSorbent, vermiculite, and activated carbon, respectively. The curves in these figures show that all samples released NOx upon heating.

As one might expect, the activated carbon sample released the most NOx. For activated carbon, NOx releases began at about 140°C (284°F) and reached a maximum at 230° (446°F).

The MagSorbent sample released NOx within two distinct temperature ranges, one reaching a maximum at about 170°C (338°F) and a second reaching a maximum at 260°C (500°F). The releases of NOx from the vermiculite sample were much smaller than from the

MagSorbent sample, but were real. Like MagSorbent, the vermiculite sample released NOx in two temperature ranges. One range reached a maximum at 260°C (500°F) and the second had a maximum above 650°C (1200°F).

The exposed internal surface area of the straight rectangular channel unit was approximately twice that of the straight circular channel unit. However, the NOx removals in both units were comparable for a given material. This observation indicates that total exposed surface area is not an important factor in determining NOx removal performance. The velocity of the gas (or the time of exposure), on the other hand, clearly did affect performance, and therefore is an important factor. For optimum performance, it appears one should make the baffled surfaces as long as possible or should maximize the total open space between baffles to decrease the velocity of gases passing through.

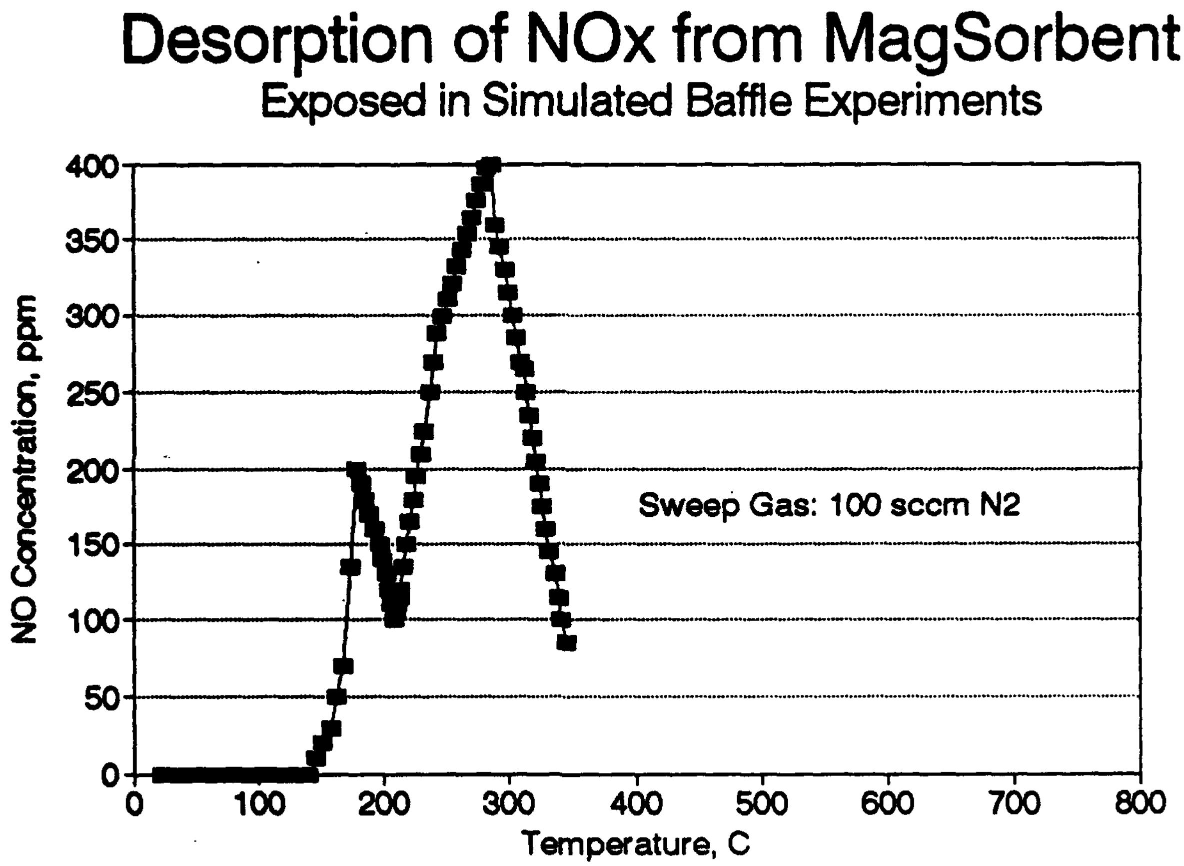

Figure 6. Desorption Curve for MagSorbent

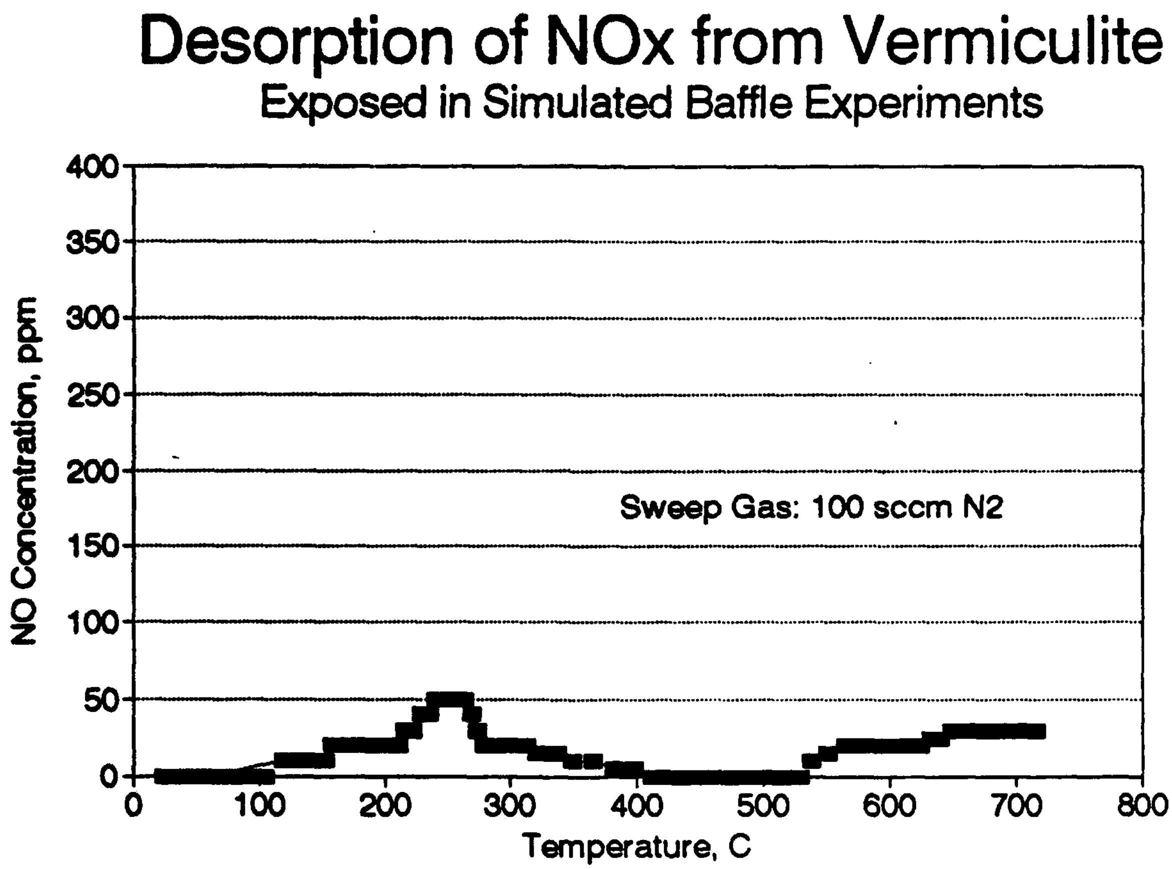

Figure 7. Desorption Curve for Vermiculite

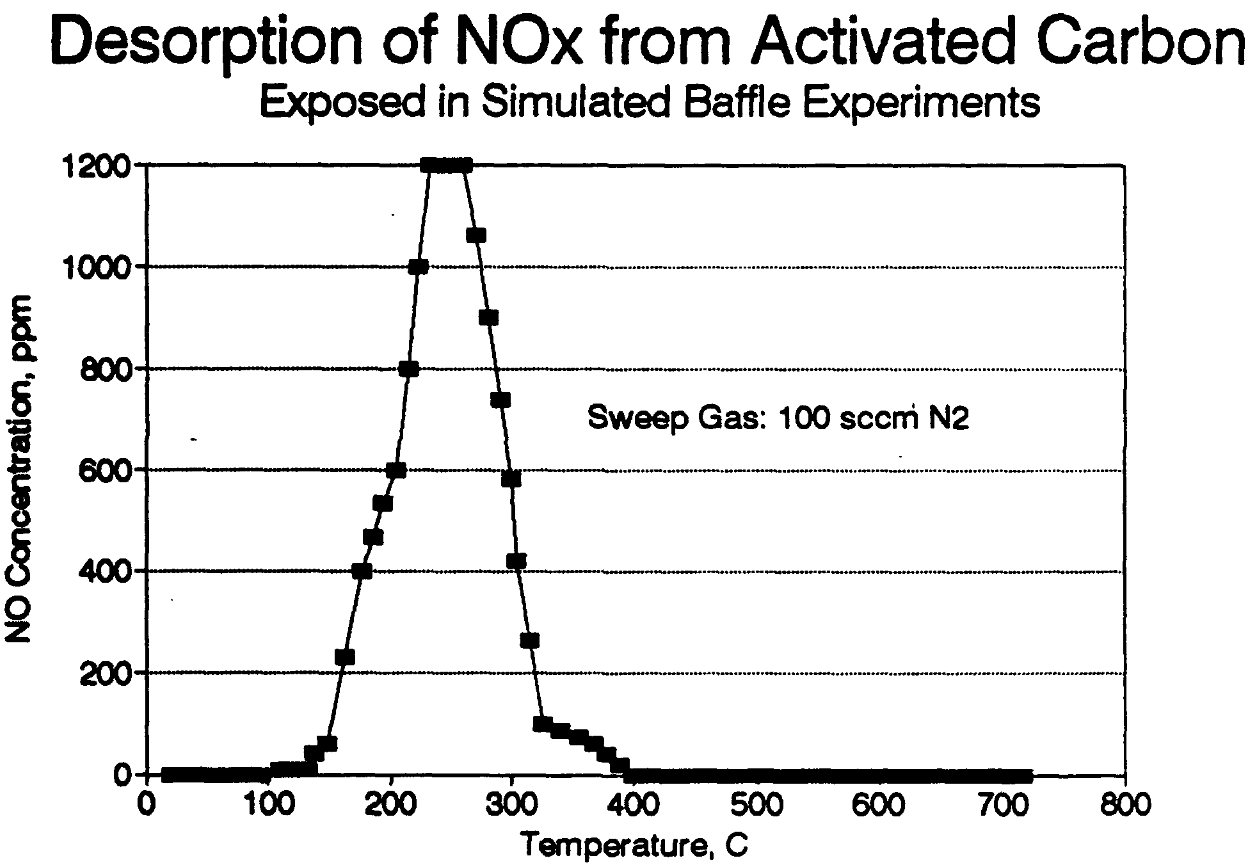

Figure 8. Desorption Curve for Activated Carbon

SECTION IV

CONCLUSIONS

On the basis of the results of this study, Sorbtech has arrived at the following conclusions:

1. The approach of lining the outside walls of sound-suppressing baffles with sorbent appears to have some merit for NOx removal, at least in the short term.

2. All three sorbents studied (activated carbon, MagSorbent, and vermiculite) demonstrated the ability to reduce NOx levels in the exhaust gases. For gas streams containing no appreciable CO, activated carbon demonstrated the highest NOx-removal efficiencies, 10 to 33 percent. MagSorbent and vermiculite, on the other hand, demonstrated relatively poor removals.

3. For low-velocity gas streams containing CO, relatively good NOx reductions, up to 30 percent or more, with MagSorbent were noted. For high-velocity gas streams with vermiculite, essentially no NOx reduction occurred.

4. Within the temperature range 70° to 350°F, there was little or no change in NOx-removal performance with increase in temperature for the three materials examined.

5. Within the velocity range 1.0 to about 40.0 fps, there was generally a decrease in NOx-removal performance with increasing gas velocity for the three materials examined. The reductions were most pronounced with activated carbon.

6. The total surface area of the test shapes and the design of the baffle surface appeared to have only a minimal effect on NOx removals. The length of the baffle, the velocity of the exhaust gas, the composition of the sorbent, and the presence of CO in the gas appeared to be the important variables affecting performance.

SECTION V

RECOMMENDATIONS

Additional studies are recommended to examine the mechanisms by which vermiculite, MagSorbent, and activated carbon reduce the levels of NOx in exhaust gases, particularly when CO is present; to determine the expected life of these materials before replacement or regeneration is necessary; to develop methods of regeneration; and to optimize the expected performance of one or all of the materials in larger-scale demonstrations.

APPENDIX

LABORATORY TEST DATA

Table 1. Test Results

RUN NO. 1

MagSorbent - Round Open Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity* (fps)	Gas NOx Level (ppm) Into Unit	Out from Unit	NOx Removal (%)
0	77	87	0.15	1.1	0	0	0.0
1	86	88	0.15	1.3	80	76	5.0
2	---	---	0.15	---	82	79	3.7
3	136	97	0.15	---	83	81	2.4
4	145	99	0.15	1.5	84	81	3.6
5	150	101	0.15	---	86	83	3.5
6	162	104	0.15	1.4	86	83	3.5
7	166	105	0.15	---	87	84	3.4
8	172	108	0.15	1.4	86	84	2.3
9	178	111	0.15	---	86.5	83	4.0
10	180	113	0.15	1.2	86	84	2.3
			Average (0-10 Min) -		84.7	81.8	3.4
			Average NOx Removal -		3.4%		
14	207	122	0.15	1.5	42	40.5	3.6
15	207	124	0.15	---	42	41.5	1.2
16	208	125	0.15	---	43	41.5	3.5
17	208	127	0.15	1.4	43.5	40.5	6.9
18	208	128	0.15	---	43	42	2.3
			Average (14-18 Min) -		42.7	41.2	3.5
			Average NOx Removal -		3.5%		

*Gas velocity in channel parallel with MagSorbent face.

Table 2. Test Results

RUN NO. 2

MagSorbent - Round Open Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity* (fps)	Gas NOx Level (ppm) Into Unit	Out from Unit	NOx Removal (%)
0	71	72	0.3	2.2	1	1	0.0
1	117	85	0.3	2.2	37	36	2.7
2	142	93	0.3	2.2	40	38	5.0
3	159	102	0.3	2.2	39	39	0.0
4	169	109	0.3	2.2	41	39	4.9
5	177	115	0.3	2.2	41	39	4.9
6	185	121	0.3	2.2	41	40	2.4
7	189	125	0.3	2.2	42	41	2.4
8	193	129	0.3	2.2	42	41	2.4
			Average (0-8 Min) -		40.4	39.1	3.2
			Average NOx Removal -		3.1%		
9	196	133	0.3	2.2	43	41	4.7
10	198	136	0.3	2.2	43	41	4.7
11	200	138	0.3	2.2	44	42	4.5
12	201	141	0.3	2.2	43	41	4.7
13	200	142	0.3	2.2	44	42	4.5
14	201	144	0.3	2.2	44	42	4.5
15	201	145	0.3	2.2	44	42	4.5
			Average (9-15 Min) -		43.6	41.6	4.6
			Average NOx Removal -		4.6%		

*Gas velocity in channel parallel with MagSorbent face.

Table 3. Test Results

RUN NO. 3

MagSorbent - Round Open Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity* (fps)	Gas NOx Level (ppm) Into Unit	Out from Unit	NOx Removal (%)
0	242	119	0.0	3.7	70	---	---
2	268	125	0.0	3.4	74	74	0.0
3	276	127	0.0	3.4	71	71	0.0
5	291	136	0.0	3.5	68	68	0.0
6	290	138	0.0	3.4	68	68	0.0
9	296	144	0.0	3.5	65	65	0.0
10	298	145	0.0	3.4	65	64	1.5
12	306	150	0.0	3.1	65	62	4.6
13	306	152	0.0	3.4	65	65	0.0
16	301	155	0.0	3.3	67	67	0.0
18	302	155	0.0	3.4	66	64	3.0
20	303	157	0.0	3.4	64	64	0.0
22	306	159	0.0	3.2	64	64	0.0

*Gas velocity in channel parallel with MagSorbent face.

Table 4. Test Results

RUN NO. 4

Vermiculite - Round Open Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity* (fps)	Gas NOx Level (ppm) Into Unit	Out from Unit	NOx Removal (%)
0	72	74	0.0	3.7	0	0	0.0
2	72	74	0.0	3.7	80	75	6.3
4	71	74	0.0	3.7	75	75	0.0
6	71	74	0.0	3.7	71	71	0.0
8	71	74	0.0	9.0	30	30	0.0
10	71	74	0.0	9.0	30	27	10.0
12	71	73	0.0	9.0	27	27	0.0
14	70	73	0.2	13.1	21	18	14.3
16	70	73	0.2	13.1	21	19	9.5
18	70	73	0.2	13.1	21	19	9.5
20	127	85	0.2	10.6	38	38	0.0
22	214	112	0.2	9.0	56	56	0.0
24	242	134	0.3	8.6	59	59	0.0
26	250	150	0.3	8.2	59	59	0.0
28	260	158	0.3	7.8	61	61	0.0
30	266	166	0.3	7.4	60	60	0.0
32	290	175	0.3	6.9	64	64	0.0
34	326	190	0.3	6.1	67	67	0.0
36	303	190	0.3	6.5	61	61	0.0

*Gas velocity in channel parallel with vermiculite face.

Table 5. Test Results

RUN NO. 5

Activated Carbon - Round Open Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Gas Temperature (°F) Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity (fps)	Gas NOx Level (ppm) Into Unit	Gas NOx Level (ppm) Out from Unit	NOx Removal (%)
0	72	72	0.0	3.8	0	0	0.0
2	72	72	0.0	3.8	74	56	24.3
4	72	72	0.0	3.8	68	53	22.1
6	72	72	0.0	3.8	67	53	20.9
8	72	72	0.0	3.8	67	52	22.4
10	72	71	0.1	8.6	36	27	25.0
12	72	71	0.1	8.6	34	27	20.6
14	71	71	0.1	8.6	33	27	18.2
16	71	70	0.1	8.6	41	35	14.6
19	71	70	0.3	14.7	24	20	16.7
21	71	70	0.3	14.7	24	21	12.5
23	71	69	0.3	14.7	22	20	9.1
25	135	80	0.3	14.3	21	18	14.3
27	207	99	0.3	11.9	22	18	18.2
29	248	115	0.3	11.9	25	21	16.0
31	263	124	0.3	11.9	24	19	20.8
33	276	134	0.3	11.4	23	18	21.7
35	282	141	0.3	10.6	23	18	21.7
37	282	144	0.3	11.0	23	18	21.7
39	300	151	0.3	9.8	23	18	21.7
42	313	157	0.3	9.8	23	18	21.7
0	84	80	0.3	15.5	52	43	17.3
5	85	80	0.3	15.5	52	43	17.3
13	88	82	0.3	15.5	46	39	15.2
18	89	82	0.3	15.5	46	39	15.2
20	91	82	0.3	15.5	44	39	11.4
23	92	83	0.3	15.5	43	38	11.6
26	114	87	0.5	20.4	32	28	12.5
28	125	90	0.5	20.4	32	28	12.5
32	154	102	0.4	18.4	31	26	16.1

Table 6. Test Results

RUN NO. 6

MagSorbent - Straight Rectangular Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Gas Temperature (°F) Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity (fps)	Gas NOx Level (ppm) Into Unit	Gas NOx Level (ppm) Out from Unit	NOx Removal (%)
0	69	70	0.0	1.0	0	0	0.0
2	69	70	0.0	1.0	63	60	4.8
4	69	70	0.0	1.0	60	60	0.0
6	69	70	0.0	1.0	60	59	1.7
8	69	70	0.0	1.0	60	60	0.0
10	69	70	0.0	2.7	30	30	0.0
12	69	70	0.0	2.7	30	30	0.0
14	91	78	0.0	2.6	39	39	0.0
16	138	97	0.0	2.6	36	36	0.0
18	157	109	0.0	2.6	36	36	0.0
20	168	118	0.0	2.6	35	35	0.0
22	175	123	0.0	2.6	35	35	0.0
24	218	134	0.0	2.2	40	40	0.0
26	237	144	0.0	2.2	41	41	0.0
28	253	152	0.0	2.2	41	41	0.0
30	352	188	0.0	2.0	44	44	0.0
32	382	214	0.0	4.4	21	21	0.0
34	349	216	0.0	5.2	24	24	0.0
36	314	210	0.0	5.2	24	23	4.2
38	302	207	0.0	5.2	24	23	4.2
40	304	209	0.0	5.2	24	23	4.2

Table 7. Test Results

RUN NO. 7

Vermiculite - Straight Rectangular Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity (fps)	Gas NOx Level (ppm) Into Unit	Out from Unit	NOx Removal (%)
0	79	80	0.0	1.3	0	0	0.0
2	79	80	0.0	1.3	52	51	1.9
4	79	80	0.0	1.3	63	60	4.8
6	79	80	0.0	1.3	77	77	0.0
8	79	80	0.0	1.3	75	75	0.0
11	79	80	0.0	1.9	54	54	0.0
13	79	80	0.0	1.9	54	53	1.9
15	79	80	0.0	1.9	54	54	0.0
17	79	80	0.0	5.2	23	23	0.0
19	79	80	0.0	5.2	23	23	0.0
21	79	80	0.2	12.1	15	13	13.3
23	79	80	0.2	12.1	13	13	0.0
25	79	80	0.2	12.1	12	12	0.0
27	129	92	0.0	1.5	51	51	0.0
29	166	105	0.0	1.5	49	48	2.0
31	213	126	0.0	1.5	48	48	0.0
33	217	130	0.0	1.5	48	48	0.0
35	304	146	0.0	1.2	65	65	0.0
37	369	166	0.0	1.2	62	62	0.0
39	318	204	0.2	5.6	17	17	0.0
41	330	216	0.2	5.6	20	17	15.0
43	343	224	0.2	5.6	20	19	5.0
45	346	230	0.2	5.8	19	19	0.0
47	340	235	0.2	14.0	15	13	13.3
49	341	244	0.2	14.9	14	13	7.1
51	345	248	0.2	14.9	14	13	7.1
53	350	250	0.2	15.3	14	13	7.1

Table 8. Test Results

RUN NO. 8

Activated Carbon - Straight Rectangular Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Gas Temperature (°F) Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity (fps)	Gas NOx Level (ppm) Into Unit	Gas NOx Level (ppm) Out from Unit	NOx Removal (%)
0	75	76	0.0	1.3	0	0	0.0
4	75	76	0.0	1.3	93	67	28.0
6	75	75	0.0	1.3	79	64	19.0
8	75	75	0.0	1.3	73	56	23.3
10	75	75	0.0	1.3	67	55	17.9
12	75	75	0.0	2.0	46	38	17.4
14	75	75	0.0	2.0	50	37	26.0
16	75	75	0.0	4.8	21	18	14.3
18	75	75	0.0	4.8	20	18	10.0
20	75	75	0.0	4.8	21	18	14.3
22	75	75	0.2	13.0	10	9	10.0
24	75	75	0.2	13.0	12	9	25.0
26	75	75	0.2	13.0	10	9	10.0
28	156	95	0.0	1.6	38	32	15.8
30	189	106	0.0	1.6	38	31	18.4
32	220	118	0.0	1.6	35	31	11.4
34	238	127	0.0	1.5	35	31	11.4
36	263	160	0.0	5.6	15	14	6.7
38	270	170	0.0	5.6	15	15	0.0
40	288	180	0.0	5.6	16	15	6.3
42	305	190	0.0	5.6	17	15	11.8
44	310	195	0.0	5.6	17	15	11.8

Table 9. Test Results

RUN NO. 9

MagSorbent - Irregular Rectangular Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity* (fps)	Gas NOx Level (ppm) Into Unit	Out from Unit	NOx Removal (%)
0	75	74	0.0	3.3-12.5	0	0	0.0
2	75	74	0.0	3.3-12.5	92	92	0.0
4	77	75	0.0	3.3-12.5	95	92	3.2
6	79	76	0.0	3.3-12.5	98	96	2.0
9	79	77	0.0	3.3-12.5	100	98	2.0
11	74	75	1.1	14.2-53.1	21	21	0.0
13	73	74	1.1	14.2-53.1	21	21	0.0
18	72	74	1.1	14.2-53.1	21	21	0.0
21	71	73	1.1	14.2-53.1	21	21	0.0
24	103	96	0.0	3.3-12.5	94	91	3.2
26	98	91	0.0	3.3-12.5	97	97	0.0
28	146	109	0.2	6.6-25.0	50	50	0.0
30	176	130	0.2	6.6-25.0	50	50	0.0
32	195	145	0.2	6.0-22.5	53	52	1.9
34	266	195	0.8	9.7-36.2	27	27	0.0
36	280	216	0.8	9.7-36.2	27	26	3.7
38	292	233	0.8	9.8-36.9	26	24	7.7
41	308	247	0.8	10.0-37.5	25	24	4.0

Table 10. Test Results

RUN NO. 10

Vermiculite - Irregular Rectangular Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity (fps)	Gas NOx Level (ppm) Into Unit	Out from Unit	NOx Removal (%)
0	75	79	0.0	1.1-4.2	0	0	0.0
2	75	79	0.0	1.1-4.2	90	80	11.1
4	75	78	0.0	1.1-4.2	90	83	7.8
6	75	79	0.0	1.1-4.2	87	81	6.9
8	75	79	0.0	1.1-4.2	89	81	9.0
10	75	79	0.0	1.4-5.2	76	67	11.8
12	75	79	0.0	1.4-5.2	78	67	14.1
14	75	79	0.0	1.4-5.2	78	67	14.1
16	75	79	0.0	4.8-18.2	61	61	0.0
18	75	79	0.0	4.8-18.2	64	64	0.0
20	75	79	0.0	4.8-18.2	67	67	0.0
22	75	80	1.1	11.2-42.0	17	17	0.0
24	75	80	1.1	11.2-42.0	17	17	0.0
26	75	80	1.1	11.2-42.0	17	17	0.0
28	132	90	0.0	1.4-5.2	52	50	3.8
30	205	100	0.0	1.5-5.6	49	49	0.0
32	236	108	0.0	1.4-5.2	49	49	0.0
34	258	119	0.0	1.4-5.2	49	49	0.0
36	304	128	0.0	1.3-4.9	55	55	0.0
38	336	137	0.0	1.3-4.9	54	54	0.0
0	71	74	0.0	4.2-15.8	61	61	0.0
5	204	152	0.8	7.3-27.5	22	22	0.0
8	248	188	0.8	7.3-27.5	21	21	0.0
11	269	212	0.8	7.3-27.5	21	21	0.0
15	289	235	0.7	6.7-25.0	21	21	0.0

Table 11. Test Results

RUN NO. 11

MagSorbent - Irregular Rectangular Channel
NOx and CO Additions

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Gas Temperature (°F) Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity (fps)	Gas NOx Level (ppm) Into Unit	Gas NOx Level (ppm) Out from Unit	NOx Removal (%)	Gas CO Level (ppm) Into Unit	Gas CO Level (ppm) Out from Unit	CO Removal (%)
0	76	78	0.0	1.1-4.2	0	0	0.0	0	0	0.0
2	76	78	0.0	1.1-4.2	80	67	16.3	59	56	5.1
4	76	78	0.0	1.1-4.2	78	66	15.4	66	54	18.2
6	76	77	0.0	1.1-4.2	78	65	16.7	68	64	5.9
8	76	77	0.0	1.1-4.2	78	67	14.1	74	60	18.9
10	76	77	0.0	1.7-6.3	67	46	31.3	68	50	26.5
12	76	77	0.0	1.7-6.3	61	43	29.5	60	47	21.7
14	76	77	0.0	1.7-6.3	63	43	31.7	62	53	14.5
17	76	77	0.3	4.8-18.2	27	18	33.3	29	25	13.8
19	76	77	0.3	4.8-17.8	28	18	35.7	30	23	23.3
29	118	83	0.0	1.8-6.6	43	43	0.0	58	49	15.5
31	162	92	0.0	1.8-6.6	42	37	11.9	53	53	0.0
33	192	102	0.0	1.8-6.6	43	36	16.3	53	49	7.5
35	211	111	0.0	1.8-6.6	42	34	19.0	58	45	22.4
37	221	120	0.0	1.8-6.6	40	34	15.0	52	49	5.8
41	233	143	0.3	5.6-21.0	20	14	30.0	25	19	24.0
43	235	149	0.3	5.6-21.0	20	13	35.0	27	19	29.6
45	230	152	0.3	5.6-21.0	20	13	35.0	25	17	32.0

Table 12. Test Results

RUN NO. 12

Activated Carbon - Irregular Rectangular Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity (fps)	Gas NOx Level (ppm) Into Unit	Out from Unit	NOx Removal (%)
0	78	78	0.0	1.2-4.5	0	0	0.0
4	78	78	0.0	1.3-4.9	69	46	33.3
6	78	78	0.0	1.3-4.9	50	40	20.0
8	78	78	0.0	1.3-4.9	50	35	30.0
10	78	78	0.0	1.3-4.9	80	60	25.0
12	78	78	0.0	1.3-4.9	66	55	16.7
14	78	78	0.0	1.4-5.2	72	58	19.4
17	78	78	0.0	2.0-7.7	65	52	20.0
19	78	78	0.0	2.0-7.3	62	49	21.0
21	78	78	0.0	2.0-7.3	63	49	22.2
23	79	78	0.1	5.2-19.6	25	21	16.0
25	79	78	0.1	5.2-19.6	25	20	20.0
27	79	78	0.1	5.2-19.6	24	20	16.7
33	119	85	0.0	1.7-6.3	51	43	15.7
35	181	101	0.0	1.7-6.3	51	40	21.6
37	213	113	0.0	1.7-6.3	48	40	16.7
39	240	122	0.0	1.6-5.9	48	40	16.7
41	255	138	0.2	4.7-17.5	26	23	11.5
43	262	150	0.2	4.7-17.5	26	23	11.5
45	285	160	0.2	4.7-17.5	26	20	23.1
46	305	167	0.2	4.7-17.5	26	21	19.2
48	316	173	0.2	4.7-17.5	26	20	23.1

Table 13. Test Results

RUN NO. 13

Activated Carbon - Irregular Rectangular Channel

Time of Run (Min.)	Gas Temperature (°F) Into Unit	Out from Unit	ΔP Across Unit (in.H_2O)	Gas Velocity (fps)	Gas NOx Level (ppm) Into Unit	Out from Unit	NOx Removal (%)
0	69	69	0.0	3.8-14.1	0	0	0.0
2	69	69	0.0	3.8-14.1	69	60	13.0
4	72	70	0.0	3.8-14.1	72	62	13.9
8	75	71	0.0	3.8-14.1	75	66	12.0
11	75	72	0.0	3.8-14.1	75	66	12.0
15	75	72	0.3	7.5-28.1	33	31	6.1
18	75	72	0.3	7.5-28.1	33	31	6.1
22	75	72	0.3	7.5-28.1	34	31	8.8
25	71	71	1.1	15.3-57.4	16	15	6.3
28	69	69	1.1	15.3-57.4	16	15	6.3
30	68	69	1.1	15.3-57.4	15	14	6.7
36	81	73	0.0	3.3-12.4	105	91	13.3
38	83	74	0.0	3.3-12.4	105	91	13.3
40	140	95	0.3	7.5-28.1	45	40	11.1
42	174	114	0.3	7.5-28.1	45	39	13.3
44	199	129	0.3	7.1-26.6	45	39	13.3
46	268	177	0.8	10.8-40.5	24	21	12.5
49	282	194	0.8	10.8-40.5	24	21	12.5
52	292	210	0.8	10.8-40.5	24	21	12.5

Table 14. Test Results

RUN NO. 14

Vermiculite - Round Open Channel
NOx and CO Additions

Time of	Gas Temperature (°F)		ΔP Across	Gas Velocity	Gas NOx Level (ppm)		NOx Removal	Gas CO Level (ppm)		CO Removal
Run (Min.)	Into Unit	Out from Unit	Unit (in.H_2O)	(fps)	Into Unit	Out from Unit	(%)	Into Unit	Out from Unit	(%)
0	69	71	0.2	10.6	0	0	0.0	0	0	0.0
3	69	71	0.2	10.6	83	80	3.6	46	44	4.3
8	68	70	0.2	10.6	80	80	0.0	46	46	0.0
11	68	70	0.2	10.6	85	80	5.9	48	46	4.2
16	68	70	0.2	10.6	83	80	3.6	48	48	0.0
18	68	70	0.2	10.6	86	83	3.5	46	46	0.0
20	68	70	0.7	20.4	43	43	0.0	25	25	0.0
22	68	70	0.7	20.4	43	42	2.3	25	23	8.0
24	68	70	0.7	20.4	40	40	0.0	21	21	0.0
27	68	70	1.3	36.8	34	34	0.0	18	17	5.5
30	68	70	1.3	36.8	33	33	0.0	17	17	0.0